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DESIGN OF FOIL IMPLOSION SYSTEM FOR PIONEER I EXPERIMENTS*

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Abstract

A foil implosion system is described that integrates an explosive flux-compression generator, a flat plate feed section with power conditioning switches, and a vacuum electrode region containing a cylindrical foil/plasma load. Power conditioning, obtained with an explosive-driven plasma compression opening switch and explosive-actuated closing switches, provides a submicrosecond multimegampere pulse for the implosion of an aluminum plasma. The flat plate section is configured for bidirectional feed to the coaxial vacuum electrodes. Important considerations in the design of the vacuum power flow region include gap failure, feed symmetry, and radial diagnostic access. The system presently accommodates a foil radius of 3 cm. Innovative foil insertion and clamping techniques are also described.

Introduction

Experiments are being conducted that employ an active, compact inductive driver for the fast J x B implosion of a thin cylindrical plasma. The driver consists of an explosive powered flux compression generator and a fast opening/closing switch combination. These Pioneer I experiments are our first attempts at coupling an explosive generator to a fast dynamic load using intermediate pulse conditioning techniques. The Pioneer I system is a close-coupled expendable system. It combines a proven driver with flat plate symmetry and a higher-symmetry coaxial feed and load. The experiments, when fully optimized, should be capable of peak load currents of 4-5 MA at input voltages of 120-150 kV for submicrosecond implosions. The Pioneer I system is being used as a test bed for the development of techniques, the validation of codes, the exercising of diagnostics and the identification of systems problems. Such experiments are preliminary to more ambitious ones that will use higher energy flux compression and switching components in cylindrical geometry for the development of an intense, pulsed soft x-ray source.

The potential for the high energy application of inductive storage/compression has been demonstrated by the Air Force Weapons Laboratory in their SHIVA program.[1] Their approach,[2] which uses capacitive storage as a primary source, is responsible for much of the relevant power flow technology and load physics. The Pioneer I system described below uses much of that experience.

The discussion here concentrates on the design and related issues for the Pioneer I system. Companion papers by Greene et al.[3] and Lee et al.[4] discuss system expectations, diagnostics, and test results.

Inductive Driver: Components and Feed

The Pioneer I system is shown in Fig. 1. The experimentally determined source characteristics of the explosive plate generator[5] are shown in Fig. 2. The lower parallel plate section is terminated by a

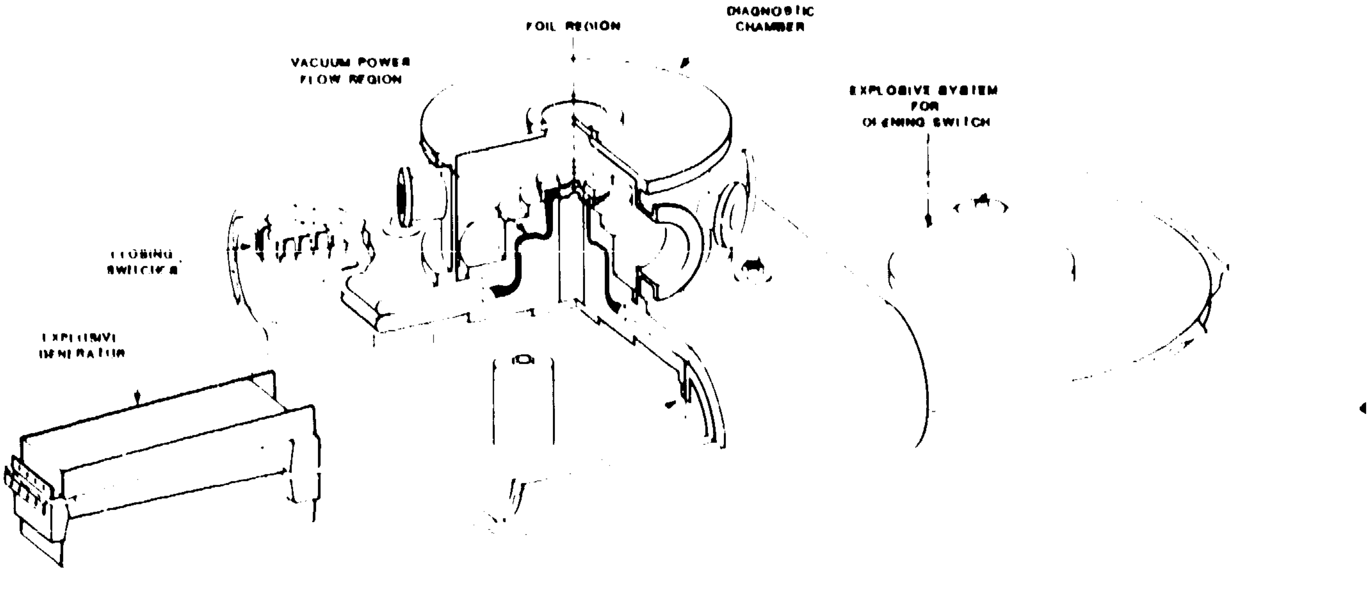

Fig. 1. Pioneer I foil implosion system.

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plasma compression opening switch, also driven by explosive. The switch geometry and characteristics are described in detail by Goforth et al,[6] elsewhere in these proceedings. The upper section is brought into the circuit through a pair of curved transitions that contain multichannel detonator-driven closing switches. The upper section also provides bidirectional feed to the coaxial vacuum power flow and load regions.

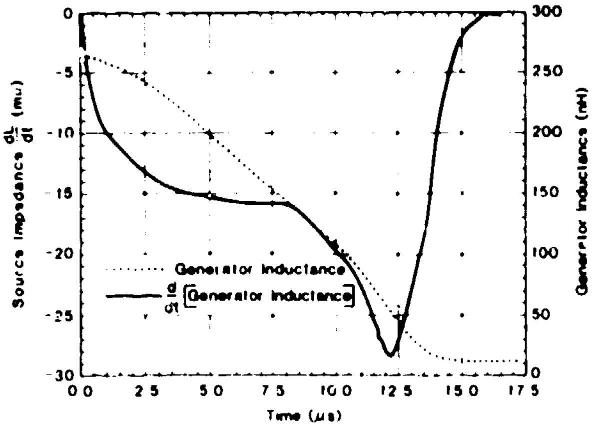

Fig. 2. Inductance and source impedance of plate generator.

The operating sequence for the system begins with the discharge of a capacitor bank through the lower part of the assembly. The discharge establishes conducting plasma in the opening switch cavities and primes the generator with magnetic energy. After injection of initial current, the explosive generator is actuated, first trapping flux in the generator volume and then compressing it to amplify current in the circuit. At an appropriate time, the plasmas in the opening switch are compressed, giving rise to a fast increase in resistance. As voltage rises across the opening switch, the closing switches are actuated to direct current into the load located in the upper part of the experiment.

The overall length of the lower biplate section is about 1.5 m. The geometry of the upper biplate is a square with dimension 0.76 m, which is also the working width for inductance considerations. These dimensions are a compromise between our desire for a low inductance, close coupled feed (< 5 nH in any direction) and convenience in fabrication. The experiment is designed to be driven at negative potential with reference ground connected to the top member of the upper biplate. High voltage is therefore confined to the inner members of the assembly.

The closing switches are shown in cutaway in Fig. 1 and in profile in Fig. 3. These switches are linear multichannel arrays, up to 20 channels per line. The arrays employ detonators which initiate explosive pellets (2 mm long and 6.1 mm diam) placed over 1.2 mm diam holes bored in 6.4 mm thick aluminum. The closing mechanism results from a jet like stem, produced by the explosive interaction, that penetrates 1 mm of polyethylene sheet in the switch gap. Limited testing has been done to quantify simultaneity. Two 20-channel arrays were tested at 20 kV DC with low current transfer. The jitter associated with closure was 20 ns for one array and 32 ns for the other. Standard deviations were 10 and 12 ns respectively. Similar testing has not been done under high current pulsed conditions, although we know that closing time is voltage dependent.

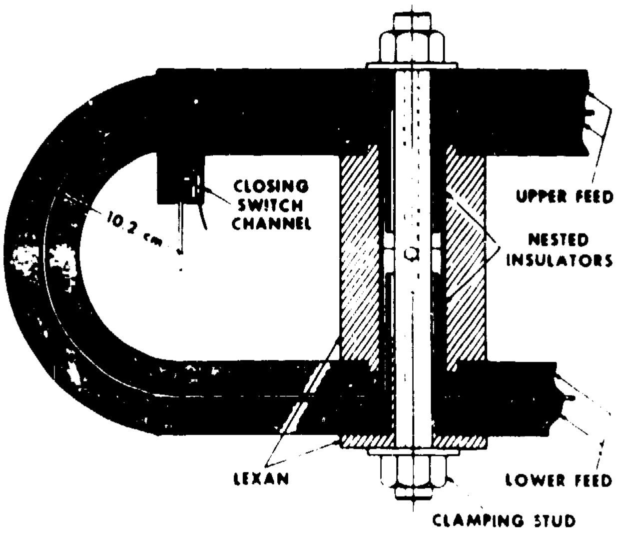

Fig. 3. Transition region from lower biplate to upper biplate showing location of closing switch array and insulated clamp.

Also shown in Fig. 3 is one of the four insulated mechanical clamps used to align the assembly to high precision. The lower biplate is separated from the upper by Lexan spacers through which threaded, steel rods are passed. Nested polyethylene insulators isolate the rods within each biplate. After careful alignment, the assembly is pulled together and locked against heavily torqued steel nuts. The air within the spacers is replaced by SF_6, which flows through holes provided in each rod. When properly assembled, axial concentricity between the inner and outer vacuum electrodes is within 75 µm; planarity between horizontal electrode surfaces at regions near the foil radius is within 25 µm.

The lower biplate is insulated with 2.5 mm of Mylar sheet. The curved transitions also have 2.5-mm gaps that are filled with various thicknesses of polyethylene switch insulation and Mylar. The upper biplate is insulated with the 2.5-mm-thick brim of the vacuum insulator and 1.25 mm of Mylar.

Vacuum Power Flow: Design and Fabrication

The design challenge for this part of our experiment is to prevent gap failure at minimum inductance in a current-density regime where magnetic insulation is not yet working to advantage. Principal failure mechanisms are conventional vacuum breakdown, ablative closure, and insulator flashover. The latter two mechanisms are driven by the ultraviolet radiation from the plasma load. Various inputs have guided the design. Electric field strengths are estimated from the two-dimensional code LAPLACE; ablative closure is predicted from MHD modelling; and ultraviolet attenuation is examined with the Air Force Weapons Laboratory's ray tracing code STREAM.

The design of the vacuum power flow geometry as presently used in our Pioneer I testing is shown in Fig. 4. The geometry is constrained radially by a 5 cm foil radius, selected to reasonably shorten implosion time, and a 17.8 cm radius for the vacuum interface. The geometry is further constrained by our intent to view implosion dynamics radially.

The convoluted vacuum gap is formed from nested aluminum electrodes. Input to the gap is across the insulator fabricated from high-density polyethylene. The current-carrying surfaces were machined, using numerical control, and hard anodized. The mounting cap, which completes the outer electrode, is fabricated from copper. An annular array of radial vanes at 10° intervals is machined in the cap using a spark cutting technique. Each vane is 1.5 mm wide. The minimum gap in the power flow region is 1.0 cm. It opens to 1.5 cm at the top of the feed and to 2.5 cm between the foil and the i.d. of the vane structure. The inductance calculated for this power flow geometry is 10.2 nH. We have considered the perturbations that this periodic vane structure would cause in the magnetic field that drives the implosion. Effects due to asymmetry in the current feed have also been examined. On the basis of an analytic model used to estimate Rayleigh-Taylor instabilities, perturbations[7] from the vane periodicity and the feed asymmetry are negligibly small for the load geometry of Fig. 4.

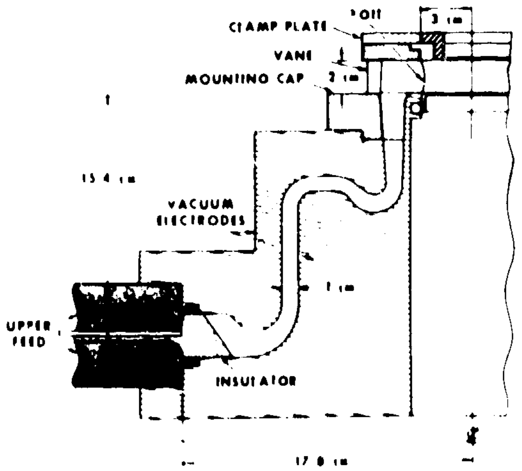

Fig. 4. Vacuum power flow and load regions of Pioneer I system.

The diagnostic chamber, shown in Fig. 1, is equipped with multiple radial ports and an upper axial port. Pumping for the system is provided by a small turbomolecular pump connected directly to one of the radial ports. Vacuum quality is better than [illegible] x 10^{-5} torr.

Load Foil: Fabrication and Insertion

Seamless aluminum foils of 200-nm thickness are presently being used in our implosion experiments. The hardware used to both fabricate the foil and insert it into the Pioneer I electrode configuration is shown in Fig. 5. Assembly of the hardware prior to foil fabrication begins by attaching the lightweight aluminum spacer to the upper mounting ring. The lower mounting ring is added and the clamp screw inserted through the assembly. A set screw is driven against the flat in the clamp screw. The clamp nut is added and lightly tightened to draw the assembly together. The essential feature of the hardware is the set screw that prevents rotation. Rotational torque tends to rip a foil during the insertion process.

Foil fabrication involves the evaporation of an aluminum/aluminum oxide composite[8] onto a seamless, polyvinylalcohol mandrel. The mandrel is first drawn onto the fabrication hardware and positioned in an evaporation chamber. A 100-nm layer of aluminum, monitored by an Auger technique, is evaporated onto the rotating mandrel. Oxygen is then pulsed into the chamber to form a 10-nm layer of Al_xO_y for strengthening. The additional 100-nm thickness of aluminum is evaporated over the oxide layer. The foil assembly is removed, the mandrel dissolved in water, and the assembly dried. Final foil thickness is determined from alpha step measurements on an adjacent witness slide. Oxygen content in a foil is estimated at about 1%. Catenation for a typical foil is estimated at < 1 mm.

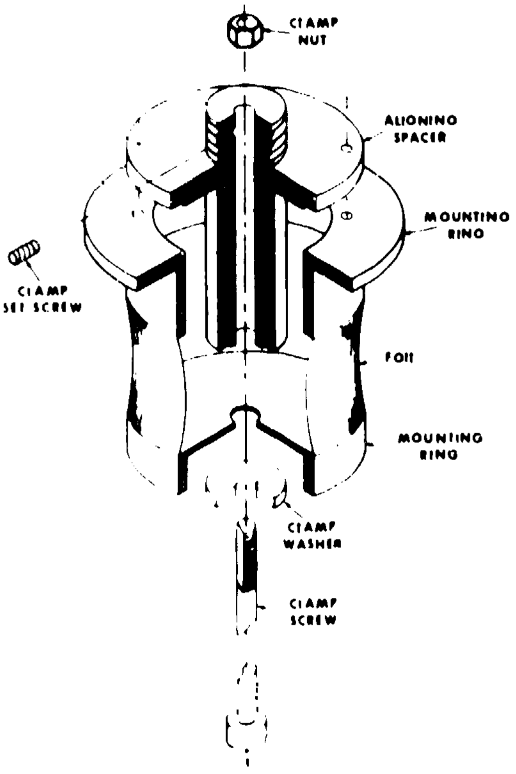

Fig. 5. Assembly for fabrication and insertion of ultrathin aluminum foils.

After fabrication of the foil, the hardware in Fig. 5 is lowered into the Pioneer I diode on guide posts not shown. Two techniques have been used to uniformly contact the lower mounting ring to the inner electrode. The first involves the expansion of a Tygon tube that is installed in the circular channel of the inner electrode immediately adjacent to the lower ring (see Fig. 4). The tube when energized with externally supplied air pressure acts as a bladder to expand a segmented copper strip, which has been spring loaded into the circular channel, against the lower ring. Our preferred technique, for the time being, employs a coil spring inserted in the circular channel which grabs the lower ring upon insertion. Both techniques center the foil. After constraining the lower ring, the clamp plate in Fig. 4 is installed to lock the upper mounting ring. Screws holding the aligning spacer to the upper ring are removed, and the clamp nut is retracted. The set screw is loosened allowing the clamp screw and washer to drop. The aligning spacer and guideposts are then withdrawn. With the hardware in Fig. 5 and the procedures just described, our insertion process has become routine and trauma free.

Conclusions

We have designed the compact but expendable Pioneer I system to drive a cylindrical plasma implosion. The system, which features explosive pulsed power, has been successfully demonstrated.[4,9] A scheme to convert a single-point flat plate drive into a bidirectional feed for a coaxial load has been successfully incorporated. Innovative techniques for the insertion and clamping of ultrathin aluminum foils have been developed and put into routine use. Future experiments will push the system for increased performance. Additional design effort will be directed at the vacuum power flow region.

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Acknowledgements

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